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Chinese Carbon Capture and Storage Technology

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Abstract. Global warming is a critical crisis confronting the world, with industrial CO_2 emissions accounting for 65% of global greenhouse gases and serving as the leading driver of the greenhouse effect. This paper focused on the development and challenges of Carbon Capture and Storage (CCS) technology in China. As the world's largest emitter of carbon dioxide, China has made substantial efforts to combat global climate change through CCS, which captures and stores CO_2 from industrial processes. The paper analyzed the technical principles of CCS, covering capture, transportation, and storage methods, while assessing their feasibility within China’s coal-dependent energy structure. Key issues such as public acceptance, legal frameworks, and cost-efficiency are also examined. The study concluded by proposing strategies to overcome these challenges and promote large-scale deployment of CCS technology, emphasizing the importance of technological innovation, policy alignment, and international collaboration. By addressing barriers to implementation and exploring innovative solutions, this paper aimed to deepen the understanding of CCS technology’s role in mitigating climate change, ultimately contributing to global initiatives for environmental sustainability and the reduction of greenhouse gas emissions.

Keywords: China; Carbon Dioxide; CCS technology.

1. Introduction

With the rapid development of the world and the swift progress of the industrial era, CO_2 emissions have soared [1-2]. According to data from the International Energy Agency (IEA), global CO_2 emissions exceeded 36.8 billion tons in 2022, reaching an all-time high. As a major industrial country, China's rapid development has inevitably led to substantial greenhouse gas emissions. Nowadays, global climate warming has become a challenging issue for the world, and China's energy sector has decided to resolutely implement Xi Jinping Thought on Socialism with Chinese Characteristics for a New Era and scientifically and orderly promote the green and low-carbon transformation of energy . Furthermore, the "14th Five-Year Plan for National Economic and Social Development of the People's Republic of China and the Long-Range Objectives Through the Year 2035" has, for the first time, included the carbon peaking and carbon neutrality (hereinafter referred to as "dual carbon") goals in economic and social development planning. The optimization and adjustment of China's carbon reduction policies have become an important research direction.

Carbon Capture and Storage (CCS) technology involves capturing CO_2 produced in industrial processes and storing it in underground reservoirs for the long term to reduce CO_2 emissions into the atmosphere. This is of great significance for mitigating climate change caused by CO_2 emissions. Currently, CCS technology is relatively mature internationally. According to the "Global CCS Project Overview," CCS projects are gradually expanding their scale. Since the operation of the first large-scale CCS project, Val Verde CO_2-EOR, at the Sharon Ridge oilfield in Texas in 1972, the total CO_2 capture capacity of CCS projects under development, construction, and operation globally has reached 361 million tons per year by July 31, 2023, representing an increase of approximately 50% compared to 2022 [3]. Moreover, extensive research has been conducted internationally on CCS (Carbon Capture and Storage) technology, covering various critical aspects. For instance, Davison and Herzog used cost analysis to compare the costs of CCS technology across three types of power plants: IGCC (Integrated Gasification Combined Cycle), NGCC (Natural Gas Combined Cycle), and PC (Pulverized Coal). Their study concluded that the operating costs of CCS projects in IGCC plants are relatively lower, and with advancements in technology, these costs are expected to decline further. IGCC also demonstrated relatively low capture costs and outstanding performance in pollutant removal, power generation efficiency, and CO_2 capture. However, its system is complex, requiring a substantial initial investment, with fixed costs reaching up to USD 1,430 per kilowatt [4]. Public acceptance of CCS technology is another crucial factor for its sustainable development. Seigo et al. [5] conducted a study analyzing 42 papers to understand public attitudes toward CCS technology, underscoring the importance of social acceptance for its successful implementation. Additionally, legal and regulatory research plays a key role in ensuring that CCS technology development aligns with existing laws. Renner et al. [6] identified that certain aspects of CCS technology could conflict with EU environmental laws, indicating the need for new regulations to address these legal gaps and facilitate better development of the technology.

Research on CCS technology can be conducted from three main aspects. First, in terms of application prospects, as early as 2006, researchers provided a comprehensive analysis of the concept, process, potential, and various influencing factors of CCS technology in China, marking the earliest and most comprehensive study on this topic in the country [7]. Additionally, previous studies examined the legal framework and future development of CCS technology's regulatory system, focusing on addressing legal challenges to promote its implementation in China . Researchers introduced the current development status and future trends of CCS technology. Second, economic feasibility studies have centered on the commercial promotion of CCS technology, cost-benefit analyses, and the economic benefits of CCS under different operational models. Researchers compared the cost-benefit of CCS under various models, concluding that "IGCC + CCS" represents the optimal approach. Lastly, technical research has largely focused on storage technology. Researchers also provided a comprehensive analysis of the geological conditions and potential storage sites for CO_2 storage in China [8].

This paper mainly focused on the development of carbon capture and storage (CCS) technology in China. It covers the technical principles of carbon capture and storage, followed by an in-depth analysis of the feasibility of this technology in China, as well as the challenges and difficulties it faces in future development. Finally, it provides development strategies to address these challenges and difficulties.

2. Main Technologies of CCS Technology

2.1. CO2 Capture

CO_2 capture can be mainly divided into three categories: post-combustion capture, pre-combustion capture, and in-combustion capture (oxy-fuel combustion). Below are the basic principles and advantages and disadvantages of these three capture methods:

(1) Post-combustion capture: This technology involves separating carbon dioxide from non-combustible gases such as nitrogen, oxygen, and water vapor in flue gas after fuel combustion. The main capture methods include chemical absorption, solid adsorption, and membrane absorption. Among them, chemical absorption utilizes alkaline absorbents to chemically react with carbon dioxide in flue gas to form salts, which are then released and regenerated under heating or decompression conditions. The advantages of this technology are high capture efficiency and wide applicability, currently used in power plants, refineries, etc. The disadvantages are increased capture energy consumption, cost, and difficulty due to the fast flow rate of flue gas per unit volume and low carbon dioxide concentration.

(2) Pre-combustion capture: This technology involves separating and capturing carbon dioxide from combustible gases before fuel combustion. Specifically, fossil fuels are gasified into a mixture of H_2 and CO, which is then converted into CO_2 through chemical reactions. H_2 and CO_2 are separated using adsorption methods, with main technical means including solution absorption, solid adsorption, and membrane separation. The advantage of this technology is that it is the most economically valuable compared to the other two capture methods. The disadvantage is its limited applicability,

restricted to integrated gasification combined cycle (IGCC) power generation systems, and requires a large footprint.

(3) In-combustion capture (oxy-fuel combustion): This technology includes oxy-fuel combustion and chemical looping combustion. Oxy-fuel combustion uses a mixture of high-concentration oxygen and carbon dioxide instead of air to react with pulverized coal in a boiler, increasing the concentration of carbon dioxide in the flue gas through flue gas recycling for easier subsequent separation. Chemical looping combustion uses oxygen carriers to allow fuel to combust without direct contact with air, producing only carbon dioxide and water, which can be directly recovered. The advantages of this technology are the ability to extract high-purity carbon dioxide, reducing the cost of subsequent carbon dioxide separation operations. The disadvantage is the high initial cost.

2.2. CO2 Storage Technologies

CO_2 storage technologies focus on safely storing captured carbon rather than emitting it directly into the atmosphere. The process generally involves three key steps.

The first step, carbon capture, uses specialized equipment or processes to capture CO_2 emissions from major sources such as thermal power plants, chemical plants, steel production, shipping, coal-fired power generation, automobiles, petrochemicals, cement manufacturing, and oilfields.

The second step is the compression and transportation of the captured CO_2. After being compressed, CO_2 is transported via pipelines, ships, or other methods to storage locations. There are three primary CO_2 transportation methods, each with distinct advantages and disadvantages. Pipeline transportation offers low costs, large capacity, long-distance coverage, and high safety, but it also has high construction costs, potential for pipeline corrosion, and risk of CO_2 leakage. Tanker transportation is flexible and has lower investment costs, but faces challenges such as intermittent supply, high costs, and risks of evaporation and leakage. Ship transportation is ideal for long distances and flexible routing, with a large transport capacity and lower costs for long hauls, but like tanker transportation, it has intermittent supply, high investment costs, and evaporation risks.

The third step is CO_2 storage. Currently, two main storage methods are used: geological and ocean storage. Geological storage, the more common method, involves injecting CO_2 into deep underground geological formations such as oil and gas fields, saline formations, or unmineable coal seams. These geological structures, typically at depths of over 800 meters, keep CO_2 in a high-density liquid or supercritical state, maintaining safe storage under high pressure and low temperature conditions. Ocean storage, on the other hand, involves injecting CO_2 into the deep sea, where seawater pressure and natural barriers prevent its release into the atmosphere. Ocean fertilization can also absorb CO_2 through marine ecosystems. Both storage methods require rigorous monitoring and assessment to ensure CO_2 does not leak and that geological stability is maintained. In conclusion, CO_2 storage technologies present a promising solution for carbon emissions reduction. With ongoing technological advancements and cost reductions, the future of carbon storage technologies looks increasingly viable for broader applications.

3. Feasibility Analysis Of CCS Technology In China

This paper analyzes the feasibility of Carbon Capture and Storage (CCS) technology in China from several perspectives.

Firstly, China’s energy structure, characterized by a "primary energy supply dominated by coal and secondary energy mainly derived from coal-fired power," provides a critical backdrop for CCS development. In 2024, China produced 4.71 billion tons of raw coal, 200 million tons of crude oil, and achieved a seventh consecutive year of increased natural gas production, reaching 232.43 billion cubic meters. Since 2023, China’s total energy consumption reached 5.72 billion tons of standard coal, with coal accounting for 55.3%, highlighting the continued reliance on coal and the strategic significance of CCS technology for China. Secondly, technical feasibility is evidenced by China’s rapid advancements in CCS technology.

Notably, the Qilu Petrochemical-Shengli Oilfield project represents China's first million-ton-scale CCS initiative. China has developed a comprehensive technical system for CCS and applied it in industries such as coal-fired power, petrochemicals, cement, and steel. According to Zhiyan Consulting, by August 2024, China had 67 operational CCUS (Carbon Capture, Utilization, and Storage) projects, capturing approximately 7 million tons of CO_2 annually. Furthermore, CCS technology benefits from strong governmental support. The Chinese government has issued various policies promoting CCS research and development, incorporating it into the country's broader socio-economic development plans as a key technology for advancing green transformation. Additionally, the market potential for CCS technology in China is vast. As one of the world's largest energy consumers and CO_2 emitters, China faces significant pressure to reduce emissions, and CCS technology is seen as a vital tool for achieving its dual carbon goals.

Lastly, the economic feasibility of CCS is improving as technological advancements reduce costs. Technologies such as enhanced oil recovery (EOR) using captured CO_2 have already been commercially implemented. Moreover, China's development of CCUS technology, which integrates a utilization component into the CCS process, opens up opportunities for new business models. For example, captured CO_2 can be converted into valuable chemicals or materials, enabling the circular use of carbon resources. In conclusion, CCS technology demonstrates high feasibility in China, and with continued technological advancements, supportive policies, and market growth, it is expected to achieve larger-scale application and development in the near future.

4. Chinese Strategy for Developing CCS Technology

Despite the broad development prospects, there are still certain issues and challenges due to technological breakthroughs and innovations, investment costs, legal frameworks, and the level of public awareness [9-10]. There are many uncertainties surrounding its large-scale implementation. The following are strategies for improvement:

(1) China needs technological innovation and research and development. China is actively researching and adopting more efficient and low-energy carbon capture technologies, including amine-based methods, membrane separation, and Direct Air Capture (DAC). These technological innovations provide strong support for the sustainable development of the CCS industry. As CCS technology matures, it can enhance capture efficiency and reduce costs. As mentioned earlier, capture technology is the highest energy-consuming and cost-generating aspect of the CCS system, accounting for two-thirds or even more of the total cost. Therefore, improving capture efficiency and reducing capture costs are the main directions of technological research and development.

(2) Promote system integration and optimization. In the various stages of carbon capture, transportation, and storage, promote system integration and optimization to improve overall efficiency and economy. Secondly, in terms of policy, China should first set goals to integrate CCS technology into its national energy and climate strategies, clarifying its important role in achieving the dual carbon goals. Incentive policies should also be formulated, such as financial subsidies, tax exemptions and reductions, and carbon trading markets, to encourage enterprises and research institutions to invest in the research and development, as well as the application of CCS technology.

(3) Improve laws and regulations. Formulate and improve regulations and standards related to CCS, including technical standards, safety standards, and environmental protection standards for carbon capture, transportation, and storage. Compared with foreign countries, the development of CCS technology in China is relatively late and has lagged behind, especially in terms of operation and operational experience. Therefore, we need to cultivate and introduce talents, support universities and research institutions in conducting education and training in CCS-related majors, and cultivate a group of high-quality professionals. We can also introduce overseas talents, attracting outstanding professionals in the field of CCS from abroad to work in China, thereby enhancing the research and development level of China's CCS technology and accelerating its development.

(4) Strengthen international cooperation by collaborating with major global economies and research institutions to jointly promote the development and application of CCS technology, and share technology and experience. Through international conferences, seminars, and other forms, share China's research and development achievements and application experiences in the field of CCS technology, listen to useful suggestions, and make improvements to promote technological development.

(5) Expand the market. Through the construction of CCS demonstration projects, accumulate experience, prove the feasibility of the technology, and lay the foundation for commercial scale. Expand the scope of application by promoting CCS technology in high-emission industries such as power, steel, cement, and chemicals, forming a diversified application pattern. Lastly, increase public awareness of CCS technology and enhance people's acceptance and support for this technology. In summary, these methods will all contribute to the development of CCS technology.

5. Conclusion

This paper underscored the critical importance of Carbon Capture and Storage (CCS) technology in China's efforts to meet its carbon neutrality goals and combat climate change. Given China's energy structure, where coal dominates, CCS technology offers a practical solution for reducing carbon emissions while maintaining industrial productivity. The study highlights that CCS technology is both technically feasible and economically viable, especially with government support and continued technological advancements. However, significant challenges remain, including the high costs associated with carbon capture, transportation, and storage. Technological innovations, such as improvements in capture efficiency and the development of cost-effective storage solutions, are necessary to make CCS more accessible on a larger scale. Additionally, the study emphasizes the need for stronger legal and regulatory frameworks to ensure the safe implementation of CCS projects. Public acceptance also plays a crucial role in the successful deployment of CCS technology, necessitating efforts to raise awareness and foster societal support. Furthermore, this research suggests that China's CCS development can benefit greatly from international cooperation. Collaborating with other countries in sharing knowledge, experiences, and technological advancements can accelerate CCS progress and make it more cost-efficient. Expanding CCS applications beyond coal-fired power plants to sectors such as petrochemicals, cement, and steel could also diversify its impact.

The study advocated for the integration of CCS into China’s broader economic and climate policies. Incentives such as subsidies, tax breaks, and carbon trading markets are critical for encouraging the private sector and research institutions to invest in CCS technology. In conclusion, with continuous advancements, supportive policies, and international cooperation, CCS technology holds great promise for helping China achieve its "dual carbon" goals and contribute to global efforts in mitigating climate change.

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